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AN ANALYSIS ON THE MEASUREMENT OF THE YOUNG MODULUS FOR COMPOSITE MATERIALS AND ITS EFFECT ON PIPE REPAIR SYSTEMS

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Abstract. *This paper aims to search for alternative techniques for measuring the Young Modulus without the use of strain gauges or extensometers and to demonstrate how different parameters can influence its value, such as number of fiberglass layers, fabrication techniques and the method used for measurement. This property seems very simple, and for that reason may have its precise calculation neglected, but the smallest variation in the defined modulus can have a huge impact on the estimation of the thickness for pipe repairs using composite sleeves. This paper presents not only different methodologies to calculate the Young Modulus, but also shows what a great impact these methods can have in system repairs and how they can lead to premature failures or to the overestimation of the repair thicknesses and consequently the increase of its costs.*

Keywords: *Young Modulus; composite materials; pipe repair; mechanics of fracture.*

1. INTRODUCTION

Normally, bidirectional or unidirectional composites are used in composite repair systems for corroded pipelines. Many studies concerning composite repair systems have been performed in the last years (da Costa Mattos et al., 2009; da Costa Mattos et al., 2014). The ISO 24817 standard defines the adequate composite thickness to assure the reinforcement or repair, and one of the essential mechanical properties necessary to obtain the composite thickness is the Young's Modulus. Because it seems simple, the adequate measurement of this property is generally neglected, and the mixture rule is adopted. Also, many experimental mistakes can lead to an inaccurate estimate of the necessary composite thickness.

Bonded strain transducers are more expensive and require a careful preparation. If many tensile tests in different conditions (environment, specimen geometry, etc.) must be performed, it would be interesting to obtain the Young Modulus using simpler, but accurate methodologies. The focus of the present study is to:

- 1) Analyze if the Young's modulus can be obtained without the use of bonded strain gauges or extensometers, using only the stroke displacement and grip distance, which is simpler and less expensive.
- 2) Study the effect of the specimen thickness, fabrication methodology (mainly if pressure is applied or not during the curing process) and grip type (stationary head with hydraulic grip and movable head with mechanical grips) on the Young Modulus and the maximum stress before failure.
- 3) Show that, although simpler measurement techniques can indeed be used to obtain the elastic properties, they can lead to wrong conclusions about the material behavior. The adequate measurement technique is important to define the proportional limit and the material behavior under non-monotonic loading histories.
- 4) Present the effects of such measurements in the calculations of pipe repair systems.

2. MATERIALS AND METHODS

2.1 Materials

Specimens made of an epoxy resin reinforced with bidirectional fiberglass layers were used in all tests presented in this paper. The epoxy resin is a Bisphenol A ether modified with reactive diluent and the hardener used was a modified polyamine. All specimens were fabricated according to the ASTM D3036 standard. They were made with four different thicknesses (8, 12, 16 and 20 layers). Also, for the specimens with 16 layers, two different types of preparations were tested, with and without pressure during the curing process.

Figure 1 shows the preparation, cure and the final specimens:



Figure 1. Preparation of the specimens.

2.2 Methods

The selected specimen geometry was a flat rectangular one, with 25 millimeters width and 250 millimeters total length. For the distance between grips was set a fix number of 172 millimeters, based on previous works done in this institution.

The following definitions are used to calculate the engineering stress σ and engineering strain ε :

$$\sigma(t) = \frac{F(t)}{A_0} \quad ; \quad \varepsilon(t) = \frac{\Delta L(t)}{L_0} \quad (1)$$

Where $F(t)$ is the axial force necessary to impose an elongation $\Delta L(t)$ at a given instant t . L_0 is the gauge length and A_0 the cross-section area. Generally, a bonded strain gauge or an extensometer are used to obtain the engineering strain. For most purposes, the extensometer gauge length L_0 should be in the range of 10 to 50 mm. In the case of a bonded strain transducer, an active gauge length of 6 mm is recommended for most materials.

Two different testing machines were used for the tensile tests: One is a Shimadzu AG-X universal testing machine with a of 100 kN capacity load cell and electro-mechanical sensors to control the longitudinal displacement, with an adaptable extensometer. The other is a Servo Pulser testing machine based on an electro-hydraulic servo mechanism that enables tests under large load or high speed to be conducted and works with a 100 kN capacity load cell.

All the tensile tests were carried out at a speed of 2 mm/min, as defined by ASTM D3036.

3. RESULTS AND DISCUSSION

3.1 Studying the Young Modulus

3.1.1 Analyzing the influence of the testing method

The first approach for this study was to analyze how the obtained results for the Young Modulus differs from one calculation method to another. Figure 2 shows the graphics obtained for the same kind of specimen but using three different ways to measure the deformation: an electro-mechanical machine with mechanic grips and a hydraulic machine with hydraulic grips, both using a 172 mm gauge length (distance between grips), and also an extensometer with 25 mm gauge length used in the electro-mechanical machine.

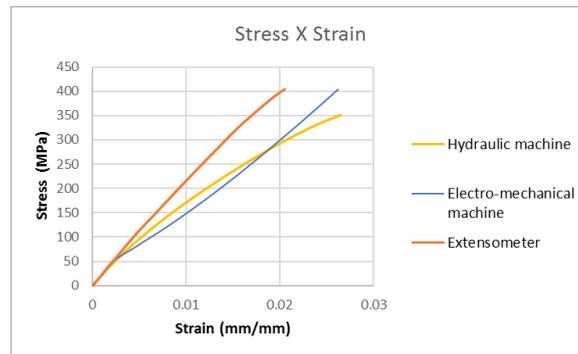


Figure 2. Different ways of measuring tension and deformation.

It is interesting to observe how the obtained curves are so different from each other for the same material, but in the initial portion, i.e. the elastic portion, all three curves are very similar within each other.

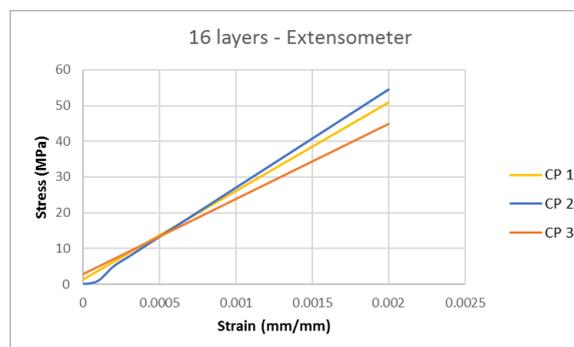
3.1.2 Analyzing the influence of the number of layers

A second observation is to analyze how different amounts of fiberglass layers affects the Young Modulus. For that purpose, were fabricated specimens with four different number of layers: 8, 12, 16 and 20. The amount of resin used in each case was proportional with the number of fiberglass layers so it wouldn't change the ratio between fiber and resin. Table 1 shows the dimensions measured for the thickness in each case:

Table 1. Thickness of the specimens.

8 layers	~ 1.5 mm
12 layers	~ 2.5 mm
16 layers	~ 3.5 mm
20 layers	~ 4.5 mm

For each of these cases, the strain was measured in three different ways: in the electro-mechanical machine using the distance between grips (172 mm), also in the electro-mechanical machine with the extensometer, and last at the hydraulic machine using the distance between grips (172 mm). Figure 3 show the graphics for the elastic portion obtained for the specimen with 16 layers in all three cases:



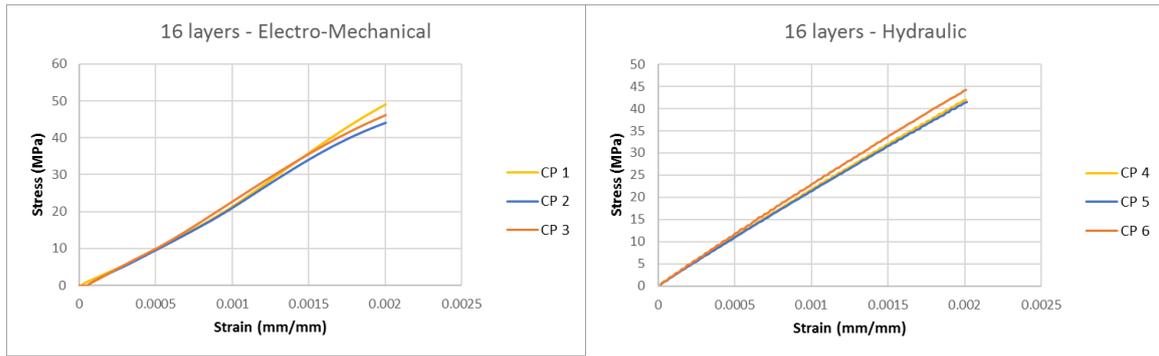


Figure 3. Young Modulus (16 layers).

As can be observed, the graphics sustained a high similarity between each other. The graphics for all the other thicknesses were very similar to the ones presented and tables 2, 3 and 4 presents a brief summation of the results obtained for each of the methods, for all tested number of layers:

Table 2. Young Modulus measured by the electro-mechanical machine (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	23439	23821	26625	24628	1740
12 layers	22748	25116	22279	23381	1521
16 layers	25357	23447	24519	24441	957
20 layers	19213	21044	22282	20846	1544

Table 3. Young Modulus measured by the extensometer (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	21982	22842	24745	23190	1414
12 layers	21249	21394	25004	22549	2127
16 layers	24705	27595	23214	25171	2227
20 layers	23081	21693	27461	24078	3011

Table 4. Young Modulus measured by the hydraulic machine (MPa).

	CP 4	CP 5	CP 6	Average	Standard deviation
8 layers	21480	23032	23218	22577	954
12 layers	22161	24292	23218	23224	1066
16 layers	20886	20532	21911	21110	716
20 layers	20067	19137	20523	19909	706

The average results found for all three methods are very similar, with a minor standard deviation, what verifies that the number of layers does not affect the Young Modulus.

3.1.3 Analyzing the influence of the preparation method

There were used two different methods for curing the specimens: In the first one, once the composite was finished, it was set on a press with 4 tons of pressure for 24 hours, time necessary for the cure to be complete. The second one was cured with no pressure on it. Although both plates were made with 16 layers of fiberglass, the one that had no pressure applied during the cure time ended up with a higher quantity of resin, what made it almost one millimeter thicker than the other one.

Figure 4 shows the graphics for the Young Modulus of the specimens made without applying pressure, while fig. 4, previously presented, shows the graphics for the specimens cured in the press.

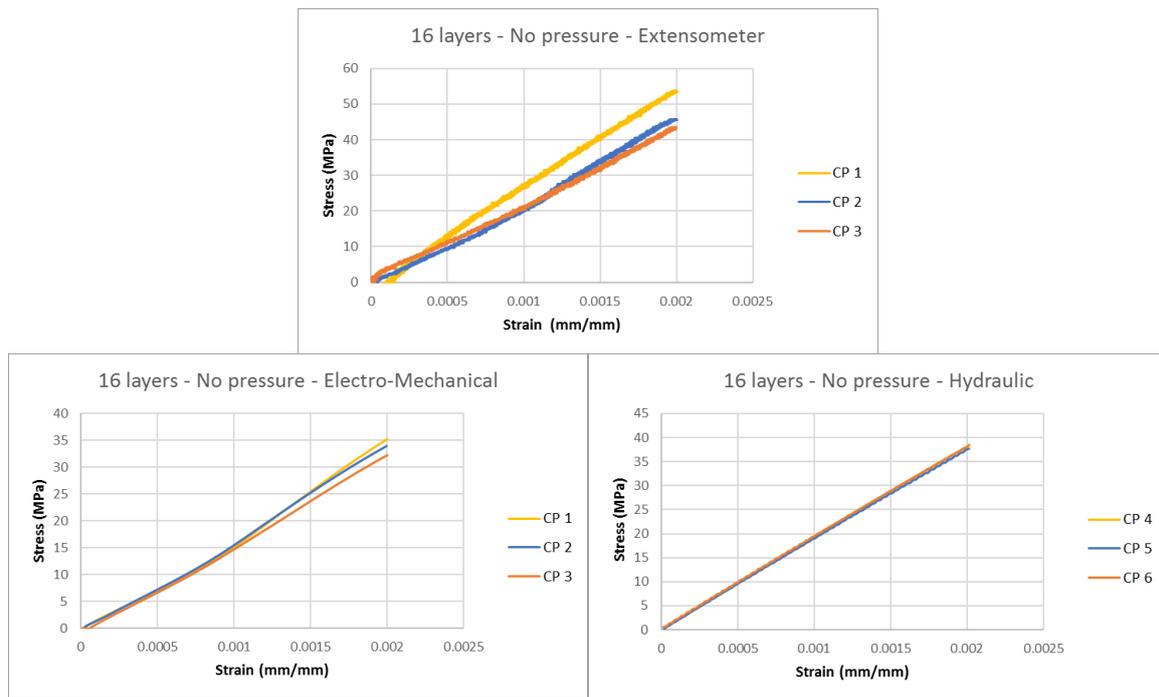


Figure 4. Young Modulus for specimens made without pressure.

Tables 5 and 6 shows a summation of the results obtained for both preparation methods:

Table 5. Young Modulus measured for the specimens cured without pressure (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
Electro-Mechanical	17997	17463	16640	17367	684
Extensometer	28135	24005	21146	24429	3514
Hydraulic	18990	18767	18963	18907	122

Table 6. Young Modulus measured for the specimens cured with pressure (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
Electro-Mechanical	25357	23447	24519	24441	957
Extensometer	24705	27595	23214	25171	2227
Hydraulic	20886	20532	21911	21110	716

From the results presented for the specimens cured without pressure, it can be observed a significant difference between the results obtained from the machines and from the extensometer. Although the values found for the extensometer were slightly dispersed, its average remained very similar to the results obtained for the specimens cured under pressure. However, the values found for the Young Modulus in both machines are quite smaller for the specimens cured without pressure, resulting in a variation of up to 35% considering the electro-mechanical machine and up to 15% in the hydraulic machine.

Such difference in the results may be explained by the distinct failure modes, once the specimens made without pressure suffered delamination during failure, unlike the ones done with the press. It is important to analyze such results, because none of the machines by itself was able to accurately measure the Young Modulus, only the extensometer was, so in cases where the cure process doesn't happen with the application of pressure, the regular stress x strain curve results in smaller results for the Young Modulus. Figures 5 and 6 presents a comparison between the specimens, where it's made very clear the distinct failures that occurred.

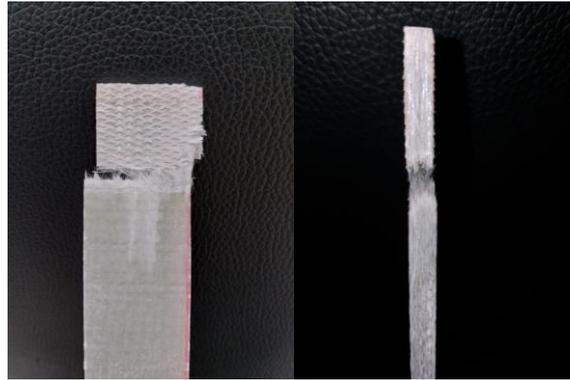


Figure 5. Failure mode for the specimens cured with pressure.

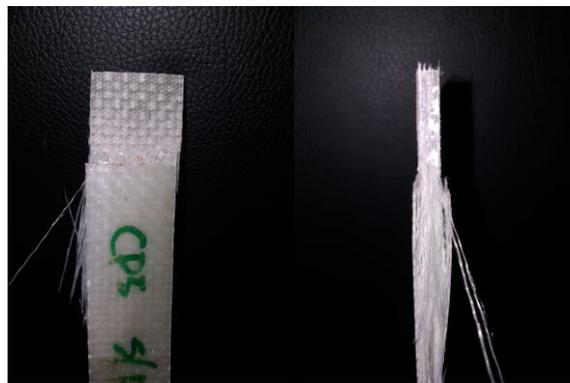


Figure 6. Failure mode for the specimens cured without pressure.

3.2 Analysing the maximum stress

3.2.1 Analyzing the influence of the number of layers

From the results obtained, the next table presents a resume of the maximum stress sustained for each of the specimens before failure, in both machines, and for each number of layers used. It isn't necessary to present the results obtained through the extensometer and through the electro-mechanical machine once the tests were the same, resulting in the same rupture forces and tensions. Tables 7, 8, 9 and 10 shows, respectively, the rupture force and the maximum stress for each of the tested specimens in both machines:

Table 7. Rupture force in the electro-mechanical machine (N).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	16115	18129	18474	17573	1274
12 layers	20632	25861	27557	24683	3609
16 layers	36495	34658	35379	35511	926
20 layers	43375	40421	37723	40507	2827

Table 8. Maximum stress in the electro-mechanical machine (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	314	349	396	353	41
12 layers	315	392	394	367	45
16 layers	439	425	404	423	18
20 layers	389	363	347	366	21

Table 9. Rupture force in the hydraulic machine (N).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	17500	16200	17600	17100	781
12 layers	25200	26100	25500	25600	458
16 layers	33200	30800	33600	32533	1514
20 layers	-	-	-	-	-

Table 10. Maximum stress in the hydraulic machine (MPa).

	CP 1	CP 2	CP 3	Average	Standard deviation
8 layers	380	381	426	396	27
12 layers	388	425	367	394	29
16 layers	350	310	370	343	30
20 layers	-	-	-	-	-

The first thing to be noticed is that there is no data for the specimen with 20 layers in the hydraulic machine. Such fact happened because the machine couldn't effectively rupture the specimen, instead the grips placed such pressure on the outer layers that they created a localized delamination causing the specimen to slip from the grips instead of breaking.

Other fact that can be perceived is that the rupture force in both machines was very similar for the specimens with the same number of layers. Such force grows almost constantly as the number of layers increases.

Finally, by observing the results obtained for the maximum stress, it is possible to realize that despite the dispersion of the results, the numbers obtained for all quantities of layers and in both machines are very similar. The dispersion in the results is most likely due to the difficulties of preparing the specimens with the same exact area, and any small variations in such parameter can cause a big difference in the calculated stress.

3.2.2 Analyzing the influence of the preparation method

Tables 11 and 12 show the results in both machines used for testing and compare the results found for the specimens cured with and without the use of the press:

Table 11. Rupture force and maximum stress in the electro-mechanical machine.

	CP 1	CP 2	CP 3	Average	Standard deviation
Rupture Force (N) - Without pressure	30909	32290	34722	32640	1930
Rupture Force (N) - With pressure	36495	34658	35379	35511	926
Maximum Stress (MPa)- Without pressure	252	284	303	280	26
Maximum Stress (MPa)- With pressure	439	425	404	423	18

Table 12. Rupture force and maximum stress in the hydraulic machine.

	CP 1	CP 2	CP 3	Average	Standard deviation
Rupture Force (N) - Without pressure	33266	34206	28561	32011	3025
Rupture Force (N) - With pressure	33200	30800	33600	32533	1514
Maximum Stress (MPa)- Without pressure	292	299	248	280	28
Maximum Stress (MPa)- With pressure	350	310	370	343	30

As can be observed, the specimens prepared both with and without pressure were able to sustain very similar loads, but due to the different areas the maximum stress until failure was significantly lower for the ones made without the application of pressure.

3.3 The effect of the measurement techniques on load-unload cycles

Following the principles of the mechanics of elastic linear fracture, it is expected that after a load-unload cycle the deformation should return to zero. To prove such theory there were performed load-unload tests for one specimen of each thickness in each of the methods presented. The maximum load determined was 70% of the average rupture load, and all

the tests were performed at the same rate as before, 2 mm/min. Figures 7 shows a comparison for the results obtained in all three methods for the specimen with 8 layers:

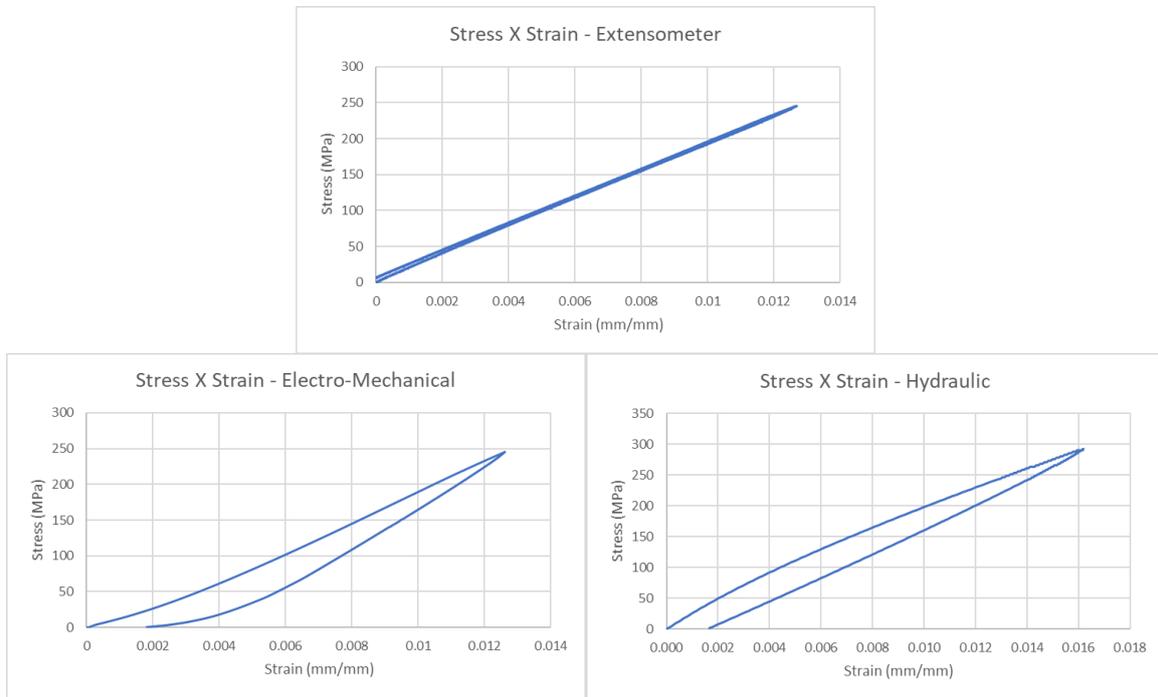


Figure 7. Load-unload cycle (8 layers).

Through the observation of the graphics, it is possible to conclude that for non-monotonic load-histories, the only reliable method is the extensometer. Due to the non-homogeneous deformation on the specimen, if the distance between grips is adopted as the gauge length (the strain field is not homogeneous nor the stress state is one-dimensional), both alternative methodologies generate a residual elongation on the specimen.

The specimens with the four number of layers had the same behavior in all three methods, so it wasn't necessary to present all the graphics obtained.

3.4 Using statistics to determine the Young Modulus experimentally obtained

Once all the tests were realized, it was set a 90% confidence interval to assure a final number for the Young Modulus experimentally determined. The software Microsoft Excel was used for the calculations and the following results were determined:

Table 13. Confidence interval for the Young Modulus.

	Value (MPa)
Margin	570
Superior limit	23495
Inferior limit	22355

For safety reasons, the inferior limit will be adopted as the as the final number: $E = 22355$ MPa.

3.5 Mixture rule

The mixture rule is still a very commonly used method to calculate the Young Modulus when it's difficult to obtain it experimentally, however it has a large error associated with it, which may result in an overestimation of the module. The following equation represents the mentioned rule:

$$E = E_f \cdot V_f + E_r \cdot V_r \tag{2}$$

Where E is the composite modulus, E_f and E_r represents the modulus for the fiber and the resin, and V_f and V_r are the volumetric fractions of the fiber and the resin. Table 14 presents the data for the fiber and the resin necessary for using the mixture rule for both the composites cured with and without pressure:

Table 14. Data for the resin and the fiber.

	Resin	Fiber
Young Modulus (GPa)	3.8	72.5
Density (kg/m³)	1160	2550
Weight – plate without pressure (kg)	0.14	0.36
Weight – plate with pressure (kg)	0.20	0.36

Through the data presented, it is possible to use the mixture law, represented by eq. (2), and calculate the Young Modulus for the material studied. Table 15 presents the obtained results:

Table 15. Results for the Young Modulus using the mixture rule.

	Young Modulus (GPa)
Plate cured without pressure	41
Plate cured with pressure	35

Analyzing the results, it is possible to conclude that not only the mixture rule calculation results in a big overestimation of the modulus, but it also shows significantly different results for the two preparation methods studied, fact that has already been proved not to influence the modulus.

3.6 Pipe repair calculation systems

To calculate the parameters for a composite sleeve to avoid plastic deformation in a thin-walled metallic pipe, it is necessary to determine the necessary thickness of the repair to impose a given contact pressure.

$$\text{If } \frac{P \cdot R}{e} > \sigma_y \quad (3)$$

The contact pressure to assure that $\frac{(P-P_c) \cdot R}{E \cdot e} = \sigma_y$ is given by:

$$P_c = P - \sigma_y \frac{e}{R} \quad (4)$$

Since the radial deformations for both the pipe and sleeve are the same:

$$\Delta R_{pipe} = \Delta R_{sleeve} \rightarrow \frac{(P - P_c) \cdot R}{E \cdot e} = \frac{P_c \cdot R}{E_L \cdot e_L} \rightarrow e_L = \frac{P_c}{(P - P_c)} \cdot \frac{e \cdot E}{E_L} \quad (5)$$

Where P is the pressure in the pipe, R is its radius, e is the pipe thickness, σ_y is the maximum stress, P_c is the contact pressure between the pipe and the sleeve, E and E_L are the Young Modulus for both the pipe and the composite sleeve, and finally e_L is the calculated sleeve thickness.

It can be observed through equation (5) that the necessary thickness for the repair is inversely proportional to the Young Modulus, so a small error in its measurement can lead to a critical error in the necessary thickness of the repair. To illustrate how grave can be such difference, it will be shown three different calculations based on the results obtained in this study: The first two using the mixture rule for que specimens cured with and without pressure, and the third based on statistics using the inferior limit of a 90% confidence interval. The Young Modulus values have already been calculated in this paper, respectively in sections 3.4 and 3.5, the hypothetical data for the pipe can be seen in tab. 16 and tab. 17 presents the obtained thickness for the three cases mentioned:

Table 16. Data used to calculate the pipe repair.

	Value
Pressure (MPa)	40
Pipe radius (mm)	76.1
Pipe thickness (mm)	7.11
Pipe Young Modulus (GPa)	200
Yield Strength (MPa)	330
Contact pressure (MPa)	9.17

Table 17. Results for the repair thickness using different methodologies.

	Repair thickness (mm)
Mixture rule - With pressure	10.35
Mixture rule - Without pressure	12.18
Confidence interval	18.91

As can be observed in the tab. 16, the difference between the results is quite significant, reaching a percentage difference of up to 83% in the required thickness. This can lead to a premature failure of the composite sleeve or an overestimation of the necessary thickness, generating a high cost repair.

4. CONCLUSION

The objective of this paper was, primarily, to show alternative techniques for measuring the Young Modulus without the use of strain gauges or extensometers, and it has been proved that for monotonic tests the results in both the electro-mechanical as in the hydraulic machine achieved very satisfactory results. However, the same cannot be said for non-monotonic cyclic due to the non-homogeneous deformation on the specimen.

It has also been proved that neither the number of fiberglass layers nor the application of pressure during the cure process directly affects the Young Modulus. But it's important to notice that the lack of pressure in the preparation does affect the failure mode by causing localized delamination in the grips, so these specimens modulus can only be measured correctly with the use of an extensometer or a strain gauge.

Finally, this paper demonstrated how the mixture rule results can deceive, once the resultant modulus is much higher than the real one, which can cause a premature failure of the repair.

5. REFERENCES

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